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Long term spatial variability in surface chlorophyll-*a* in the southeastern Arabian Sea

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Original Article

Abstract

Southeastern Arabian Sea bordering the southwest coast of India is a dynamic region influenced by the seasonally reversing monsoon system. Phytoplankton biomass of the surface waters of this region is distinctly influenced by the changes in different physical forcing mechanisms. In this paper, the variability in the phytoplankton biomass and its offshore extent in the southeastern Arabian Sea during summer monsoon season was analysed using the merged satellite chlorophyll-*a (chl-a)* concentration data provided by Ocean Colour Climate Change Initiative (OC CCI) during the last two decades from 1998 to 2017. The highest chl-*a* concentrations near the coast were observed during the summer monsoon season of 2002 and 2009-2011. Years with low chl-*a* concentration appeared to increase from 2012 onwards, with 2013 and 2016 showing an exception. The zonal extent of high chl-*a*, which on average was up to 75 °E was found to extend westwards up to 73 °E from the coast in recent years. The increase in surface chl-*a* concentration is a regular phenomenon during the summer monsoon season, the offshore extent of which is influenced by prevailing physical forcing mechanisms.

Keywords*: Phytoplankton, chl-a, summer monsoon*

Introduction

Southeastern Arabian Sea bordering the southwest coast of India is a highly productive region of the northern Indian Ocean, especially during the summer monsoon season. The fishery of this region is of importance both economically and as a major food source to the people of Kerala and neighbouring states. Southeastern Arabian Sea is influenced by the seasonally reversing monsoon winds and ocean surface currents (Shankar *et al.*, 2002; Schott and McCreary, 2001). West India Coastal Current (WICC) that flows southward during April-September and poleward during November-February is the major coastal current in the southeastern Arabian Sea (Shankar *et al.*, 2002; Schott and McCreary, 2001; Shetye *et al.*, 1991; Shetye, 1998).

Chlorophyll-*a (chl-a)* is the major photosynthetic pigment present in all phytoplankton, and its concentration is used as a proxy for phytoplankton biomass (Yoder and Kennelly, 2003; Pettersson and Pozdnyakov, 2013). In the tropics, where there is no inadequacy in sunlight, it is the nutrient availability that limits the phytoplankton biomass in the upper ocean (Moore *et al.*, 2013). Coastal upwelling caused by alongshore winds, open ocean upwelling driven by Ekman pumping, entrainment due to wind stirring at the base of the mixed layer and horizontal advection due to ocean currents are the processes that bring nutrients to the surface of the ocean

(Vinayachandran *et al.*, 2004). Tropical cyclones can also alter the chl-*a* concentration of the region depending on its intensity and duration (Smitha *et al.*, 2006). Coastal upwelling during summer monsoon in the southeastern Arabian Sea is a major phenomenon that influences the phytoplankton biomass of this region (Bakun *et al.*, 1998). Upwelling off the southwest coast of India is influenced by different physical forcing mechanisms, namely, monsoon winds, alongshore wind stress and remote forcing from Rossby and Kelvin waves which vary across the latitudes (Smitha *et al.*, 2008). Seasonal variations in the upwelling processes off the southwest coast of India were first studied in detail by Johannessen *et al.* (1981). Haugen *et al.* (2002a) analysed the seasonal circulation and coastal upwelling off the southwest coast of India, and showed that the upwelling is strongest off Cochin and Quilon in the southeastern Arabian Sea. Upwelling along the southwest coast of India is prominent between 8-14ºN (Smitha *et al.*, 2014). A reduction in upwelling off the southwest coast occurs during El Nino years (Haugen *et al.*, 2002b). Coastal waters of Kerala–an integral part of the Malabar upwelling zone is an important fishing region for small pelagics (Menon *et al.*, 2019).

Surface chlorophyll-*a* concentration in the southeastern Arabian Sea is highly variable in time and space depending on the physical forcing mechanisms (Ravichandran *et al.*, 2012; Smitha *et al.*, 2019) that influence the primary production. In the present study, spatial variations in surface chl-*a* concentration and its offshore extend particularly in the southeastern Arabian Sea during the period 1998-2017 have been analysed using a merged ocean colour data from satellite observations, and the possible causes are discussed.

Material and methods

The merged monthly surface chl-*a* concentration at 4.0 km resolution from the Ocean Colour Climate Change Initiative (OC CCI) dataset, Version [3.1], European Space Agency, available online at http://www.esa-oceancolour-cci.org (Sathyendranath *et al.*, 2017, 2018) for a twenty year period from 1998 to 2017 was used for the analysis. The dataset was created by band-shifting and bias-correcting MERIS, MODIS and VIIRS data to match SeaWiFS data and merging the datasets (Product User Guide–ESA CCI 2017). Being the merged data, chl-*a* data from OC-CCI provide the best coverage compared to individual satellite observations of the ocean colour.

The analysis was restricted to the part of southeastern Arabian Sea (approximately at 73-77ºE and 7-13ºN) that forms the coastal and offshore waters of Kerala state. The depth of waters in this region varies from very shallow near the coast to between 1000-2000 m along 73ºE. Waters beyond 200 m depth are considered as offshore waters. Seasonal climatology of chl-a concentration was computed from the monthly data for 1998 to 2017. Four seasons were chosen based on the influence of monsoon on the study area, and were, a) winter (Dec-Feb), b) pre-monsoon (Mar-May), c) summer monsoon (Jun-Sep), and d) post-monsoon (Oct-Nov). The hovmoller plots of chl-*a* concentration from May to September was constructed using monthly data, for the region 73-77ºE averaged over the latitudes 8-13ºN in the southeastern Arabian Sea to analyse the offshore extent of high concentrations of chl-*a* during the summer monsoon season.

Results and discussion

The seasonal variations in the spatial distribution of surface chl-*a* concentration during 1998-2017 in the southeastern Arabian Sea are shown in Fig. 1. During winter monsoon and pre-monsoon seasons, chl-*a* concentration in the southeastern Arabian Sea was low, especially in the offshore areas (beyond

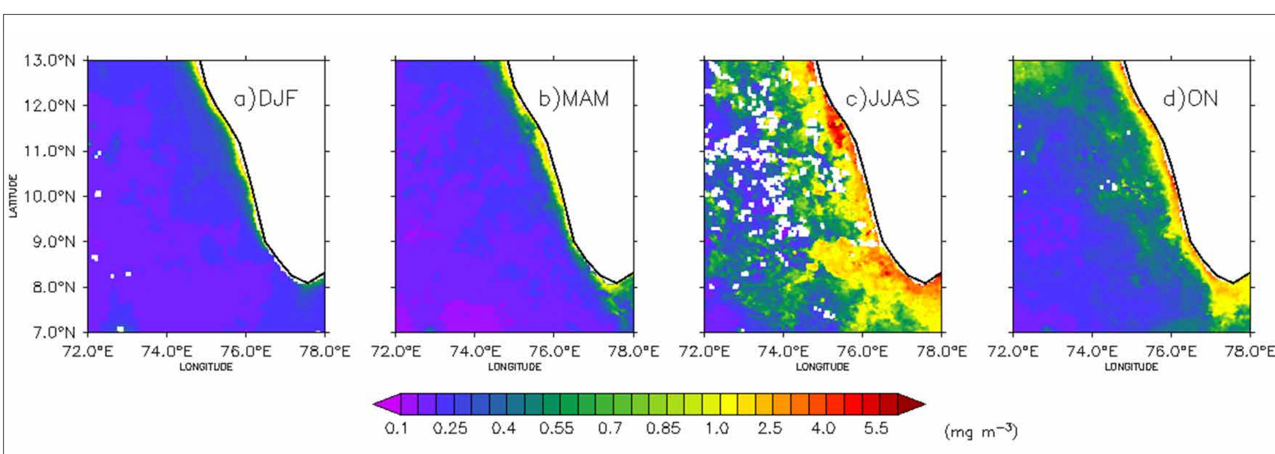

Fig. 1. Seasonal climatology of chl-*a* concentration (mg m^{-3}) during a) winter (Dec-Feb), b) pre-monsoon (Mar-May), c) summer monsoon (Jun-Sep), and d) post-monsoon (Oct-Nov) in the southeastern Arabian Sea during 1998-2017.

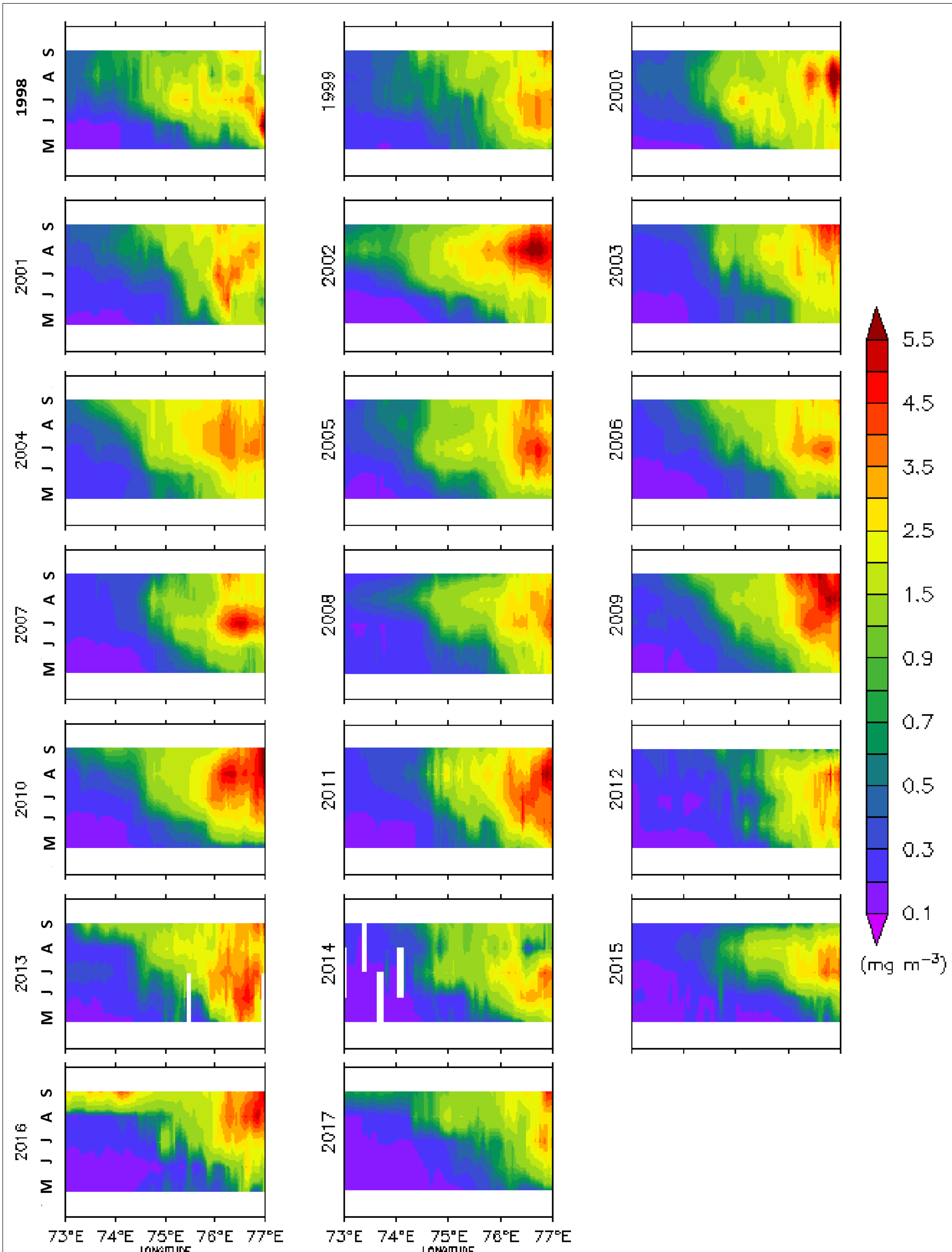

Fig. 2. Hovmoller plots of chl-*a* concentration (mg m^{-3}) along 73oE-77°E averaged over 8°N-13°N from May to September in the southeastern Arabian Sea.

75°E), where it was less than 0.4 mg m^{-3}. During summer monsoon season from June to September, when the surface current is southward, coastal upwelling occurs in this region. Upwelling increases the phytoplankton biomass, and high concentrations of chl-*a* were observed in the southeastern Arabian Sea during this time. In the open ocean, chl-*a* concentration increased up to about 3mg m^{-3}, whereas near the coast, chl-*a* concentration was as high as 6 mg m^{-3}. This high chl-*a* concentration decreased to below 3 mg m^{-3} during the post-monsoon season that followed. It is clear that a substantial increase in phytoplankton biomass occurs during summer monsoon in the southeastern Arabian Sea, which is evident from the high chl-*a* concentration during this season (Fig. 1).

Chl-*a* concentration in the southeastern Arabian Sea for the region 73-77°E averaged over the latitudes 8-13°N, from May to September of 1998-2017 are shown in Fig. 2. Highest concentrations of chl-*a* were observed after the initiation of monsoon and were found to dissipate by September except for a few years. The highest concentrations of chl-*a* near the coast were observed during the summer monsoon season of 2002, and 2009-2011. Chl-*a* concentration was lowest near the coast during 1999, 2006, 2008, 2012, 2014, 2015, and 2017. It was observed that, in general, the frequency of years with low chl-*a* concentration appeared to increase from 2012 onwards, with 2013 and 2016 being exceptions. The inter-annual variations in the zonal extent of high chl-*a* westward into the Southeastern Arabian Sea from the coast during summer monsoon season are evident in Fig. 2. During 2016, high chl-*a* extended westward to 73°E from the coast; 2002, 2004, 2010, 2013 and 2017 also experienced high offshore zonal extent compared to other years. The westward extent of high chl-*a* was lowest during 2003, 2007, 2011, 2012 and 2015.

Various physical forcing mechanisms influence the offshore extent of high chl-*a* from near the southwest coast of India. Smitha *et al.* (2019) showed that strong offshore Ekman mass transport (-1400 kg m^{-1} s^{-1} to -1500 kg m^{-1} s^{-1}) occurred during summer monsoon season in 1998-2011 in the southeastern Arabian Sea reaching as high as -2000 kg m^{-1} s^{-1} in 2010, indicating the presence of upwelling along the coast. Inter-annual variability in the offshore transport influenced the upwelling intensity and consequently the surface chl-*a* concentration. Jayaram *et al.* (2010) showed that weakening of alongshore winds reduced the upwelling intensity during 2005-2007, leading to a decrease in chlorophyll. He also showed that upwelling decreased during El Nino years 1997-1998. Discharge of nutrient-rich riverine water into coastal regions during summer monsoon also contributes to the increase in chl-*a* concentration in the southeastern Arabian Sea (Shafeeque *et al.*, 2019).

Southeastern Arabian Sea is a region coming under the influence of southwest monsoon. Apart from the nutrient availability, surface chl-*a* of this region is influenced by the seasonally varying monsoon winds, coastal currents, alongshore wind stress, and remote forcing from Rossby and Kelvin waves that modify the coastal upwelling. The analysis of twenty year data of surface chl-*a* concentration from satellites has shown that, the increase in surface chl-a concentration is a regular phenomenon supported mainly by the coastal upwelling during the summer monsoon season. However, the zonal extent of high chl-*a* concentration is linked to the strength of prevailing physical forcing mechanisms like upwelling and surface advection.

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